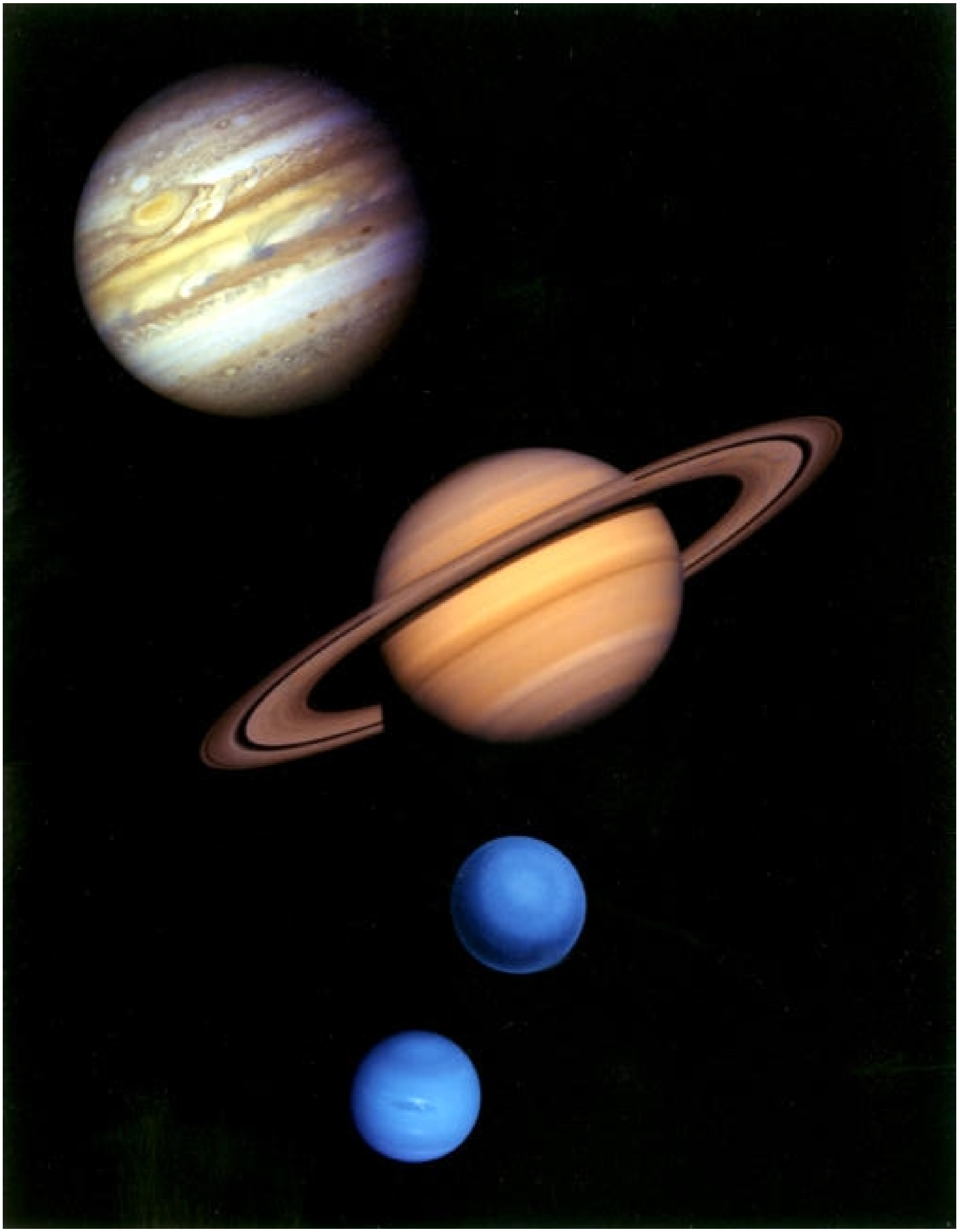

4

Giant Planets: Keys to Solar System Formation

The giant planet story is the story of the solar system. Earth and the other small objects are leftovers from the feast of giant planet formation. As they formed, the giant planets (Figure 4.1) may have migrated inward or outward, ejecting some objects from the solar system, pushing some into their parent stars and swallowing others. Smaller than stars, which have their own nuclear furnaces, the giant planets contain ~95 percent of the planetary mass of the solar system. Their hydrogen-helium atmospheres are similar to those of cooled-down mini-Suns, but their rock-ice cores may resemble those of terrestrial planets.

The differences in composition and internal structure among the giant planets reveal differences in how they formed. The "gas giants" Jupiter and Saturn are mostly hydrogen and helium. These planets must have swallowed a portion of the solar nebula intact. The "ice giants" Uranus and Neptune are made primarily of heavier stuff, probably the next most abundant elements in the Sun—oxygen, carbon, nitrogen, and sulfur. The core of each giant planet is likely the "seed" around which it accreted nebular gas.

Giant planets are laboratories in which to test our theories about geophysics, plasma physics, meteorology, and even oceanography in a larger context. Jupiter's bottomless atmosphere, with its 300-year-old storms and 500-km/h winds, piques our interest because it is so different from Earth's atmosphere. The giant planets' enormous magnetic fields and intense radiation belts test our theories of terrestrial and solar electromagnetic phenomena. The rings are puzzles, each ring system different from the others, reflecting different origins and environments. So far, the main lesson of applying theories developed for Earth to the giant planets is humility.

Giant planets are also our link to the cosmos. Many have been found around other stars. We know something about their orbits and masses, and we will soon know the radius, temperature, albedo, and partial composition for several of these objects. To interpret these data, we must understand the giant planets in the solar system. The two data sets are complementary. Extrasolar giant planets tell us how unusual we are—How many other stars have planets and possibly planetary systems like our own? The solar system's giant planets provide calibration standards. We can study them in situ, and we can calculate what they would look like from the distance of a nearby star. Together these two lines of research address the questions, Where did we come from? Where are we going? Are we alone?

FIGURE 4.1 *(facing page)* A montage of the solar system's four giant planets. Shown to scale, they are *(top to bottom)* Jupiter, Saturn, Uranus, and Neptune. Courtesy of NASA/JPL.

UNIFYING THEMES FOR STUDIES OF THE GIANT PLANETS

Giant planets may be studied as whole objects whose formation affected everything else in the solar system, as meteorological laboratories, as ringed worlds surrounded by pulsating magnetospheres, and as standards for calibrating observations of planets around other stars. The ideas discussed in this section are encompassed by the following three themes:

- Origin and evolution,
- Interiors and atmospheres, and
- Rings and plasmas.

ORIGIN AND EVOLUTION

Isaac Newton (1642-1727) used the motions of the Galilean satellites to determine Jupiter's mass. William Herschel (1738-1822) was aware that Jupiter's density was anomalously low. In the 20th century it became clear that only the lightest elements, hydrogen and helium, could account for the low density. The inferred H/He ratio was similar to that of the Sun. From spectroscopy of H_2 and CH_4 came the inference that the C/H ratio at Jupiter is similar to that of the Sun. These studies gave rise to the solar composition model of giant planets: take a piece of the Sun, cool it down to planetary temperatures, and you have a giant planet like Jupiter or Saturn.

Modified Solar Composition Model

The solar composition model does not work for Uranus and Neptune, which are twice as dense as Saturn even though they are smaller and therefore suffer less self-compression. Their densities are consistent with a mixture of water, methane, and other ices at high temperatures and pressures. Since oxygen and carbon are the third and fourth most abundant elements in the Sun after hydrogen and helium, this led to the modified solar composition model. It starts with a mixture of elements similar to that of the Sun, but then the hydrogen, helium, and other noble gases are blown away. Stars like the Sun go through an active ("T Tauri") phase when they are young. The powerful stellar winds during the T Tauri phase are capable of blowing the gases out of the system. The mixture that remains has solar composition except for the missing gaseous component. If the nebula is too hot, the ices too are lost, and only the rocks and metals remain. This modified solar composition model is supported by meteorite composition, in which the elements that form solids at planetary temperatures are present in solar proportions.

Timing is critical. Giant planets have to form before the solar wind sweeps the gases out of the solar system. That might explain the difference between the ice giants, Uranus and Neptune, and the gas giants, Jupiter and Saturn. Giant planets form faster at the orbits of Jupiter and Saturn, where the density of the solar nebula is large and collisions are more frequent. Perhaps Uranus and Neptune were just starting to accumulate gases when the T Tauri solar wind blew the gases out of the solar system.

The time that it takes to produce a Jupiter-sized object depends on how it forms, and here some uncertainty exists. The slow way is to first accrete a rock-ice core of approximately 10 Earth masses. Such a core could form by precipitation of less volatile materials as the solar nebula cools. The solid particles settle to the equatorial plane of the circumsolar disk and then coalesce by collisions. The dense solid objects are able to attract gas once they reach the critical size of about 10 Earth masses, but the rate is limited by how fast the growing object can radiate its energy. The fast way to form a Jupiter-sized object is by hydrodynamic instability. Somewhere in the solar nebula the density reaches a critical value, and the mixture collapses from its own gravitational self-attraction. Stars form this way when the density in giant molecular clouds reaches a critical value. A Jupiter-sized object formed by the second process (without a core) would be similar to a brown dwarf—a substellar object, insufficiently massive to sustain thermonuclear reactions in its core.

The way to choose between these hypotheses is to determine if all the giant planets have cores. Three out of four do. Jupiter is the uncertain one.[1] Measuring the size and mass of Jupiter's core is therefore a major objective.

Volatile Abundances

The temperature of the solar nebula at various distances from the Sun is critical in determining which compounds were solid and therefore likely to be incorporated into each giant planet and which were not. The Galileo probe found that carbon, nitrogen, sulfur, argon, krypton, and xenon are enriched by similar amounts, two to four times solar abundance. This result was unexpected, because the different elements are not equally volatile. One theory is that all the volatiles condensed together at temperatures below 30 K, at or beyond the orbit of Neptune, and then migrated in to Jupiter's position.[2] Another theory is that the volatiles were trapped in the form of clathrate hydrates in the feeding zone of Jupiter while the nebula was cooling down.[3] The first explanation says that oxygen should also be enriched by a factor of two to four. The second explanation requires a larger enrichment for oxygen (O/H at least eight-times solar abundance), because the clathrate hydrate is mostly water ice and holds only a limited fraction of other molecules.

Unfortunately, the Galileo probe did not go deep enough to measure the planetary abundance of water. The probe entered one of the dry downdrafts, which apparently extend down well below cloud base at 5 to 7 bars—at least to the 24-bar depth at which the probe signal was lost. The other condensables, ammonia (NH_3) and hydrogen sulfide (H_2S), were depleted at cloud base but approached constant values at the deepest levels. H_2O was still increasing with depth at the deepest levels. Measuring the water abundance in Jupiter's atmosphere is thus a major objective.

Cooling History

Models of the interiors predict that giant planets cool slowly. They should still be radiating substantial amounts of internal energy, and indeed, all but Uranus have measurable amounts of heat emerging from their interiors. Either Uranus cooled faster than the other giant planets did and its interior is now cold, or it is cooling more slowly, in which case the interior is hot but the heat cannot get out. For instance, a layered structure with the high-density material near the center would inhibit convection. Uranus is the only giant planet that spins on its side. Whether this unique feature has anything to do with the low heat flux is not known. The 98° obliquity is evidence that the final stage of planet formation was a chaotic process involving collisions of Earth-sized objects capable of altering the angular momentum of bodies the size of Uranus. A gentle rain of small planetesimals would not do it.

Generally, the internal heat radiated by the planets today is compatible with calculations of their cooling histories. The uncertainty centers on possible internal gradients in composition, the extent of convection zones, the equation of state, and the possible gravitational separation of hydrogen and helium as an additional source of internal energy. Internal structure is revealed in the gravity field. The equation of state is studied in the laboratory. And the separation of hydrogen and helium leaves its mark on the He/H ratio in the atmosphere today. The separation can occur only in Jupiter and Saturn, whose internal pressures are so high (>2 to 3 Mbars) that hydrogen becomes a liquid metal. It is thought that a helium-rich phase will precipitate out of the hydrogen-helium metallic mixture when the temperature drops below a critical value. Helium drops settle toward the center of the planet, leaving the layers above depleted in helium. Jupiter, because of its greater mass, cools more slowly and is just entering this stage, according to the calculations. Saturn, which has less mass, has cooled down far enough that its atmosphere should be significantly depleted in helium.

The Galileo probe measured the atmospheric He/H ratio for Jupiter. The value was higher than that obtained from Voyager remote-sensing observations but agreed with the best estimates of solar composition. In other words, precipitation of helium has not yet produced significant depletion on Jupiter. This raises questions about the interpretation of Voyager remote-sensing observations for both Jupiter and Saturn. For the latter, remote sensing is all we have, and it seems to imply that significant depletion has occurred. The Cassini Infrared Spectrograph will resolve helium lines and provide additional data; however, a probe into Saturn's atmosphere would settle the issue.

Extrasolar Giant Planets

An impressive fraction (~5 percent) of stars surveyed to date show evidence of planets. This number and the mass range will increase as more sensitive detection methods come online and planets with longer-period orbits weigh in. The discovery of giant planets in highly eccentric tight orbits (radii <1 AU) around other stars is revolutionary, because it shows that some planetary systems are very different from our own. There is clearly an observational bias to the results, because massive objects close to their stars are easier to detect by current methods. But the results imply either that giant planets can form in the high-temperature environment close to their parent stars, or that they form farther out and migrate in.[4] Either way, the implications are profound. Giant planets can migrate, provided they interact with comparable masses at different orbital radii. Objects in different orbits repel each other: to conserve angular momentum when energy is dissipated, the inner object moves inward and the outer object shifts outward. A giant planet that moves inward may have expelled other giant planets, which are now wandering through interstellar space. It will either expel or devour any terrestrial planets that are in its path.

How can the study of Jupiter, Saturn, Uranus, and Neptune contribute to the study of giant planets around other stars? The solar system provides ground-truth. The extrasolar giant planets have clouds in their atmospheres.[5] Clouds lead to precipitation and release of latent heat. The giant planets close to their parent stars have large day-night temperature gradients. The temperature gradients lead to winds, which affect the temperature field. Clouds, precipitation, temperature gradients, and winds are meteorological phenomena. We know something about these things from studying Earth and other planets. The observations of extrasolar planets—mass, radius, temperature, and composition—will be difficult to interpret unless we draw on our knowledge of giant planets in the solar system. Even that knowledge is incomplete, so further exploration is vital.

Important Questions for Origins and Evolution

Important questions about the origin and evolution of giant planets can be divided into those specifically relating to the solar system's giants and, more generally, those relating to extrasolar planets and brown dwarfs.

Important questions for the solar system's giant planets include the following:

- How did the giant planets form?
- Does Jupiter have a rock-ice core?
- What are the elemental compositions of the giant planets?
- What are the internal structures and dynamics of the giant planets?
- What are the orbital evolutionary paths of the giant planets?

For extrasolar giant planets and brown dwarfs, the important questions are these:

- Around what types of stars are giant planets found?
- Are multiple giant planets common in stellar systems?
- In what ways do giant planets differ from brown dwarfs?
- What are the properties of extrasolar giant planets (radii, effective temperatures, compositions, clouds, moons, winds, magnetic fields, heat flows)?
- How can we use the giant planets in the solar system to calibrate spectroscopic observations (optical, infrared, radio) of extrasolar giant planets?

Future Directions

As identified by the Giant Planets Panel, the most important directions for research on the origin and evolution of giant planets for the next decade are as follows:

• *Probing Jupiter's interior with gravity and magnetic field measurements from polar-orbiting spacecraft.* As with Earth, one can probe the interior with tools from geophysics that utilize seismic, gravity, and magnetic observations. Two kinds of oscillations are relevant: acoustic modes excited by convection or other interior dynamics, and tidal modes excited by the satellites. The tidal bulges show up in the planet's gravity field, which affects the spacecraft orbit. A spacecraft in a low-periapse polar orbit around Jupiter could detect the satellite-induced tides and also improve the determination of the axisymmetric terms in the gravity field. Both measurements contain information about the core.[6] The magnetic field structure provides information about convection in the deep interior, and may also contain a signature of a solid core, in analogy with Earth's magnetic field, which contains the signature of the solid inner core.[7]

• *Measuring Jupiter's deep atmospheric composition with multiple entry probes and microwave remote sensing.* Probes that operate down to the 100-bar pressure level at a variety of latitudes are needed. Remote sensing at wavelengths greater than 10 cm can detect water at depths down to hundreds of bars. The combination of probes and remote sensing is needed to provide both ground-truth and global context. The water abundance bears on how the giant planets got their volatile elements and whether significant migration of planetesimals occurred in the early solar system. It is important to measure the volatile abundances for all the giant planets, beginning with Jupiter.

• *Acquiring and interpreting Earth-based observations of solar system and extrasolar giant planets.* The effects of clouds, winds, and chemistry on the spectra of solar system giant planets need to be determined, taking into account the orientation of the planet with respect to the Sun and the observer. This information will enable us to expand the scope of comparative planetology to include extrasolar giant planets and brown dwarfs.

INTERIORS AND ATMOSPHERES

The giant planets do not have surfaces in the usual sense, but they have what amounts to the same thing from the point of view of an external observer: a barrier to both remote sensing and direct probing. With currently foreseeable technology, this occurs near the 100-bar pressure level. Below this level, properties must be inferred, just as properties of Earth's interior are inferred from near-surface measurements. The methods of inference are the same for any planet; the interiors of the giant planets are relatively unknown only because near-surface data are relatively sparse compared with data for the terrestrial planets. The distinction between interior and atmosphere is largely an operational one at the giant planets, and the two domains are probably more intimately coupled in the giant planets than in the terrestrial planets precisely because the giants lack a conventional surface.[8-11]

Interior Structure

Present models of giant planet interiors are constrained by observed properties, including planetary mass, radius, shape, rotation period, heat flow, gravitational moments, magnetic moments, and elemental composition.[12] The first five of these observable properties are known to sufficient accuracy; the last three are not. Laboratory measurements and theoretical modeling of the properties of hydrogen, helium, and trace elements at very high pressures also provide critical constraints for interior models. Previous spacecraft measurements have provided many of the observable parameters needed for the development of meaningful interior models. However, the uncertainties in both observational constraints and high-pressure material behavior are such that the interior density and temperature structure, the variation of composition and phase state with depth, and the size of a dense central rock-ice core (or even its existence, in the case of Jupiter) cannot be ascertained with confidence.

Our present view of the interiors of Jupiter and Saturn divides each planet into three distinct regions: a dense central rock-ice core with a mass of up to 10 Earth masses at Jupiter and 6 to 17 Earth masses at Saturn, a fluid metallic hydrogen region at pressures greater than about 2 Mbars, and an outer shell of molecular hydrogen.[13] The question of the presence or absence of a dense core at Jupiter is a key missing link in our understanding of Jupiter's interior structure and hence its formation history. Other key unknowns include the nature of the phase transition between metallic and molecular hydrogen, and the presence or absence of "radiative zones" where the deep atmosphere is not fully convective.

Uranus and Neptune are distinct from Jupiter and Saturn in that the former contains a much larger fraction of elements heavier than hydrogen and helium. Their interior structures are more uncertain. Three-layer models have been developed for these planets that include a small central "rock" core, an extensive "ice" region comprising most of the planet, and a methane-rich hydrogen-helium gas envelope. (In this context, "ice" means a mixture of volatile elements whose original form was water, methane, ammonia, and other ice-forming molecules but whose present form is fluid rather than solid and is probably not composed of intact molecules.) The small internal heat flux observed at Uranus may imply that parts of the interior are neither convective nor homogeneous.

Clouds and Composition

Though we still do not know what trace chemicals give the clouds of the gas giants their familiar colors, we have learned a great deal about the bulk composition and structure of their visible atmospheres from Earth-based and spacecraft-based remote sensing.[14] Different wavelengths probe different levels of the atmosphere, and this fact has been exploited to place constraints on the pressure levels, bulk compositions, and other properties of the various cloud and haze layers. The clouds of Jupiter and Saturn are thought to comprise three distinct layers, composed of ammonia at the top, ammonium hydrosulfide in the middle, and a water-solution cloud at the bottom. Analogous cloud decks may also exist at the ice giants, Uranus and Neptune, with the addition of a methane cloud at high altitudes and perhaps a hydrogen-sulfide cloud rather than an ammonia cloud just below.[15] The Galileo entry probe at Jupiter, while confirming many of the results of earlier remote-sensing observations, found little or no evidence of the expected water and ammonia clouds in the 1- to 5-bar pressure range,[16] probably as the result of entering an anomalous atmospheric hot spot. The resolution of this uncertainty is critical not only to our understanding of Jupiter's origin and evolution, as described in the previous section, but also to jovian meteorology.

The giant planet atmospheres are so cold that volatile species such as water, hydrogen sulfide, and ammonia condense. Methane is sufficiently volatile to be present as a gas throughout the upper atmospheres of the giant planets, though it too can partially condense at Uranus and Neptune. Methane molecules are broken apart at high altitudes by ultraviolet solar photons and by precipitating magnetospheric charged particles, and the fragments can react to form more complex hydrocarbon molecules, producing the array of organic molecules that have been observed in the upper atmospheres of the giant planets. A better understanding of this process may provide clues to how heavy organic molecules, including biogenic molecules, originated on early Earth. At Jupiter and Saturn, ultraviolet photons can penetrate to levels where ammonia, phosphine, and perhaps sulfur-bearing gases are present, giving rise to additional photochemistry. Studying these photochemical and thermochemical processes at the giant planets will guide the interpretation of spectra obtained from brown dwarfs and extrasolar giant planets.

An extended layer of haze particles envelops the upper atmospheres of the giant planets. The hazes are probably produced by auroral chemistry in the polar regions and by photochemistry throughout the upper atmospheres. Global high-altitude winds may carry polar hazes to lower latitudes. The haze is interesting not only because of its influence on atmospheric optical properties, thermal structure, and global circulation, but also because of the possibility of synthesis of unusual and complex organic molecules.

The impact of Comet Shoemaker-Levy 9 on Jupiter in 1994 dramatically illustrates the fact that new material is being introduced into giant planetary atmospheres. The externally supplied oxygen from comets, interplanetary dust, and satellite/ring debris is observed as H_2O and CO_2 in the upper atmospheres, and provides clues about the exchange of material between different parts of the solar system.

Thermal Structure

Just above the clouds lies the tropopause, the coldest layer of the atmosphere. Below this level the temperature increases with depth in a manner that is generally consistent with upward convective heat transport from an internal source. Above the tropopause, the temperature increases with height as the atmosphere is increasingly exposed to solar radiation. However, the observed increase of temperature in the stratosphere is greater than predicted on the basis of solar absorption alone, especially at Neptune, implying additional heating mechanisms.

In the upper stratosphere, molecular diffusion begins to affect atmospheric composition as the density of species heavier than hydrogen falls off rapidly with height. Because these heavier molecules (primarily hydrocarbons) are responsible for cooling the stratosphere by infrared radiation, the temperature rises rapidly with altitude, reaching a plateau of 400 to 1000 K in the thermosphere. The thermospheric temperatures at all giant planets are higher by a factor of two to four than would be expected on the basis of solar extreme-ultraviolet (EUV) heating.[17] Additional high-altitude heat sources are clearly operating. Possibilities include ionospheric Joule heating, charged particle precipitation, and dynamo action.

In the upper atmospheres of the giant planets, the impact of EUV solar photons and magnetospheric charged particles produces ionization, as it does on Earth. The finite electrical conductivity of the ionosphere gives rise to spectacular and dynamic auroral displays that reveal the electrodynamic coupling of the atmosphere with the magnetosphere and with the embedded satellites. As at Earth, ionospheric structure is affected by upper-atmospheric winds, magnetic-field structure, and electric fields induced by motions of plasma. In contrast to Earth, however, planetary rotation plays a dominant role in driving and shaping the upper atmosphere and ionosphere. Spacecraft radio occultations have revealed dramatic spatial (and probably temporal) variations of ionospheric structure at all giant planets, and the relative roles of chemistry and dynamics in producing the observed behavior are not well understood.

The upper atmospheres of the giant planets provide natural laboratories where we can test and refine our understanding of ionospheric structuring and auroral processes that occur under very different boundary conditions at Earth and elsewhere in the universe.

Winds

The cloud patterns are constrained by winds that blow parallel to lines of constant latitude. Instead of one eastward jet stream in each hemisphere, as at Earth, Jupiter has six or seven. The large-scale weather patterns are remarkably stable. The Great Red Spot has been in existence since at least 1664 and possibly much longer.[18,19]

Remarkably, the winds do not decrease as one moves outward in the solar system—Neptune's winds are 3 times stronger than Jupiter's, even though the power per unit area, both from sunlight and from internal heat, is about 20 times less at Neptune than at Jupiter.[20]

Principal questions revolve around the depth of the winds, the role of internal heat versus solar heat in driving them, and the mechanisms that maintain them. For instance, the Great Red Spot and the large jet streams regularly devour smaller spots, but where the smaller spots get their energy is still a mystery.

Atmospheric dynamics is intimately connected with thermal structure and composition. The energy sources for atmospheric dynamics include internal heat, solar insolation, and, at the highest levels, auroral Joule heating and charged-particle precipitation. The internal energy source evidently dominates atmospheric dynamics at and below the cloud level, and the influence of rapid planetary rotation is obvious in the preponderance of zonal (east-west) winds.

Condensation, evaporation, and transport of cloud-forming species also drive the meteorology of the giant planets through their effect on pressure gradients and the redistribution of energy, primarily in the form of latent heat. The Galileo orbiter observations of water-rich convective storms associated with lightning and cyclonic shear zones have shed new light on the role of moist convection in the maintenance of zonal jets on Jupiter; thus, knowing the abundance of water is a major objective for jovian meteorology.[21]

The zonal jets are visually prominent at the gas giants Jupiter and Saturn and less so at the ice giants Uranus and Neptune.[22-25] At Jupiter, zonal wind speeds (at the cloud level) are greatest at the boundaries between the lighter-colored "zones" of upwelling warmer atmosphere and the darker-colored "belts" of sinking cooler atmosphere. Wind maxima on Saturn are shifted relative to the banded contrasts, and the wide prevailing eastward equatorial jet has wind speeds reaching ~500 m/s, a significant fraction of the local sound speed. Uranus and Neptune, by contrast, have a prevailing westward wind near the equator and eastward winds at high latitudes, with top speeds again in the range of several hundred meters per second. The existence of such winds at Uranus is particularly puzzling in view of the fact that Uranus, unlike the other three giants, apparently has no significant internal heat source and a highly asymmetrical pattern of solar heating. In the other giants, large-scale vortices in the wind pattern revealed by cloud patterns have lifetimes ranging from months to decades in most cases, to centuries (at least) in the case of Jupiter's Great Red Spot. The longevity of these structures is not understood.

At the Galileo probe entry site, the zonal winds increased with depth, lending support to the hypothesis that the zonal jets extend deep into Jupiter's atmosphere.[26] Further measurements of deep atmospheric winds and interior structure are needed to determine how the observed atmospheric winds relate to motions, including possible nonuniform rotation, in the deep atmospheres and interiors of the giant planets.

Key Questions

Important questions about the interiors and atmospheres of giant planets include the following.

Interiors

- What is the nature of convection in giant planet interiors?
- How does the composition vary with depth?
- What is the nature of phase transitions within the giant planets?
- How is energy transported through the deep atmosphere? Do radiative layers exist?
- How and where are planetary magnetic fields generated?

Atmospheres

- What energy source maintains the zonal winds, and how do they vary with depth?
- What role does water and moist convection play?
- How and why does atmospheric temperature vary with depth, latitude, and longitude?
- What physical and chemical processes control the atmospheric composition and the formation of clouds and haze layers?
- How does the aurora affect the global composition, temperature, and haze formation?
- What produces the intricate vertical structure of giant planet ionospheres?
- At what rate does external material enter giant planet atmospheres, and where does this material come from?
- What can organic chemistry in giant planet atmospheres tell us about the atmosphere of early Earth and the origin of life?

Future Directions

The most important directions for research on the interiors and atmospheres of giant planets for the next decade are identified as follows:

- *Resolving fine-scale structure of the gravity and magnetic fields to elucidate the interior structure and the mechanisms of energy transport, magnetic-field generation, and convection within Jupiter.* The acquisition of high-order gravitational and magnetic moments, combined with satellite tides and possibly observations of acoustic oscillations within the atmosphere, will enable us to "image" the deep atmosphere and interior of Jupiter. Deep winds, if they are strong enough, will show up in the gravity field, because their centrifugal forces cause a rearrangement of masses in the deep interior.[27] These observations will provide critical constraints for models of interior structure, energy transport, fluid motions, and magnetic-field generation that have far-reaching planetary and astrophysical applications. Improved observational constraints will qualitatively enhance our understanding of planet formation and evolution and our ability to understand similarities and differences among our own giant planets, extrasolar giant planets, and brown dwarfs.
- *Measuring condensable-gas abundances (H_2O, NH_3, CH_4, and H_2S), temperature, wind velocity, and cloud opacity down to the 100-bar pressure level at Jupiter.* The Galileo probe provided critical information on

elemental abundances in Jupiter's atmosphere, but the limited depth and unusual location of its entry prevented a definitive measurement of the deep tropospheric water abundance. The water abundance is especially critical, not only because it distinguishes among different planet-formation scenarios, but also because condensation of water and the resulting release of latent heat drive atmospheric dynamics. The Galileo measurement of ammonia abundance is also uncertain, owing to experimental problems related to the behavior of ammonia within the mass spectrometer. Ammonia is a critical cloud-forming molecule in the atmospheres of Jupiter and Saturn, and remote sensing of its abundance has yielded contradictory results. Multiple in situ probes and microwave sounders can resolve these issues. Multiple probes can also provide clues to many outstanding questions about atmospheric temperature profiles, tropospheric dynamics, and cloud structure.

• *Acquiring Earth-based telescopic observations of atmospheric composition, structure, clouds, circulation, aurorae, and acoustic oscillations.* Earth-based (or orbital) observations at high spectral and spatial resolution can reveal the three-dimensional distributions of composition, temperature, and winds. These three variables are intimately related. Composition affects the absorption of solar radiation and the re-emission of infrared radiation, thus regulating the thermal structure. Composition and thermal structure affect condensation and release of latent heat, thereby affecting the wind pattern. The winds in turn affect composition and thermal structure by transporting material and heat. To understand how these interconnected processes operate, we need simultaneous observations of temperature, composition, and winds. This is difficult even at Earth, let alone at the giant planets. Previous telescope and spacecraft observations have put several pieces of this complex puzzle in place, but three-dimensional information is still limited. Greater access to large ground-based and space-based telescopes and advances in instrument technology in the next decade should greatly improve the situation. Observations of global acoustic oscillations, although difficult to obtain, are of particular interest because they shed light on interior structure.

• *Performing laboratory and theoretical studies of the behavior of matter under the extreme conditions present in giant planet interiors and atmospheres.* The thermodynamic, kinetic, radiative, and spectral properties of the relevant gases and ices, and the high-pressure equation of state of the relevant hydrogen-helium mixtures are critical to the interpretation of data on both solar system and extrasolar giant planets. Observations need to be combined with theoretical models in order to understand the underlying physical and chemical processes. Laboratory data are critical for analyzing observational data and planning future observations.

RINGS AND PLASMAS

Disks are ubiquitous in the universe, and the solar system's giant planets provide numerous examples amenable to in situ study. These range from visible rings composed of macroscopic objects dominated by gravity, to fully ionized plasma disks dominated by electromagnetic forces, with intermediate cases ("dusty plasmas") where both forces are competitive. The diversity of present-day disk structures at the giant planets offers glimpses into the various stages of solar system formation and other astrophysical processes.

At first glance it is less than obvious that studies of planetary rings will tell us anything about astrophysical disks because of the great mismatch in the relevant spatial and temporal scales on which they operate. Nevertheless, great similarities exist. Most of the underlying physics is scale-invariant, and while it is true that there are important differences between circumstellar disks and rings—for example, the presence of gas in early types of the former and the absence of gas in the latter—their dynamics are essentially the same. Moreover, the study of the dynamics of a disk of particles in the absence of gas provides one essential ingredient in understanding the dynamics of a disk of particles in the presence of gas.

Rings

Among the solar system's four known ring systems, more differences than similarities exist. Saturn's spectacular rings contain by far the most mass of all the rings. Uranus's narrow dark strands are interspersed with small, dusty particles. Jupiter's rings are exceptionally tenuous, and Neptune's rings contain possibly long-lived arc structures. The complexity and variety of structure in the various ring systems, as revealed in the Voyager images and occultations, came as a complete surprise.[28]

The theoretical life span of any of the observed ring systems is much shorter than the age of the solar system. Angular momentum transfer between rings and nearby satellites causes ring particles to fall inward, as does gas drag from the upper reaches of the planet's atmosphere. Interaction of small charged grains with magnetospheric particles and fields can produce inward or outward migration as well as erosion. Continual bombardment by interplanetary particles should darken the rings. Although the rings of Uranus are indeed quite dark, those of Saturn are as bright as fresh ice.

Where did rings come from in the first place? Are they leftover bits of material that did not get swept up into the planet or satellites? Are they the result of the catastrophic destruction of a satellite? Are they remainders of an errant comet that strayed too close to the planet and was torn apart by tidal forces? Or are they continuously replenished by material sputtered from nearby satellites by magnetospheric ions? Knowledge of ring dynamics and particle properties can help to answer these questions.

Recent studies have identified complex gravitational interactions among the rings and their retinues of attendant satellites. There are elegant examples of Lindblad and corotation resonances (two different types of eccentricity resonances first invoked in the context of galactic disks), electromagnetic resonances, spiral density waves and bending waves, narrow ringlets that exhibit internal modes due to collective instabilities, sharp-edged gaps maintained by tidal torques from embedded moonlets, and tenuous dust belts created by meteoroid impact on or collisions among parent bodies. These processes can account for some of the features observed within the ring systems and in so doing can provide the beginning of an explanation for the survival of the rings beyond their predicted life spans.

The composition, size, and shape of the particles remain major unknowns. Infrared spectroscopy and microwave radiometry reveal that Saturn's rings are mostly water ice. Different regions of the rings show noticeable color variations on all scales. The compositions of the rings of Jupiter, Uranus, and Neptune are unknown but apparently different from one another. The jovian ring system shares the reddish color of the nearby satellite Amalthea, but the brightness of the particles is unknown because their scattering cross section is unknown. The uranian rings are nearly colorless, and those of Neptune are so dark that nothing is known about their color.

The study of extrasolar protoplanetary disks can be influenced by studies of planetary rings in the solar system. The concept of the migration of bodies due to angular momentum exchange with surrounding material was first advanced in the ring context and is now a mainstay of planetary formation models. The fine structure of planetary rings with embedded bodies has motivated and guided studies that have application to disks of much larger scale.

Plasmas

The giant planets have redefined our concept of planetary magnetospheres. Unlike the terrestrial planet magnetospheres (Earth and Mercury), the giant planet magnetospheres are internally driven, powered by planetary rotational energy that is extracted by plasma of internal origin.[29] Jupiter's magnetosphere (Figure 4.2) is the largest and the most rapidly rotating and therefore the most powerful and the most different from Earth's. Jupiter's rotational energy is extracted and dissipated by plasma originating in Io's volcanoes. The transport and energization of this Iogenic plasma gives rise to an astonishing variety of remotely observable emissions across the electromagnetic spectrum from radio to x-rays.[30] Most of these emissions have strong spin-period modulations that are presumably analogous to those of astrophysical pulsars.[31]

Major unknowns include the mechanism(s) by which Io injects magnetospheric plasma and the way(s) in which this plasma is energized and transported outward to power the magnetosphere and ultimately to generate a planetary wind. These processes leave distinctive footprints in the planetary auroral emissions that are resolvable from Earth or Earth orbit. However, in situ measurements at low altitudes and high latitudes are needed to provide the key for extracting information about magnetospheric processes from Earth-based auroral images (Figures 4.3 and 4.4).

Saturn's magnetosphere is a smaller analog to Jupiter's, but more complicated because the internal sources of plasma are multiple and widely dispersed. Saturn is unique in the solar system in having a magnetic dipole moment that is almost exactly aligned with its spin axis. Reports exist of pulsar behavior at Saturn which, although

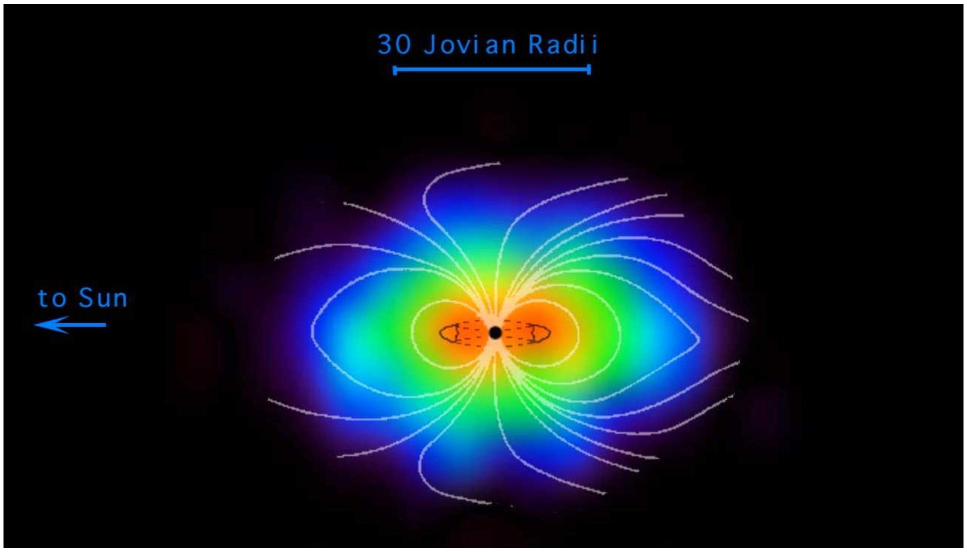

FIGURE 4.2 Jupiter's vast magnetosphere as imaged from a distance of 10 million km by the ion and neutral-atom camera aboard the Cassini spacecraft during its Jupiter flyby in December 2000. Also shown, schematically, is Jupiter's magnetic field and, to scale, the Io torus and Jupiter itself. Courtesy of NASA/JPL/APL.

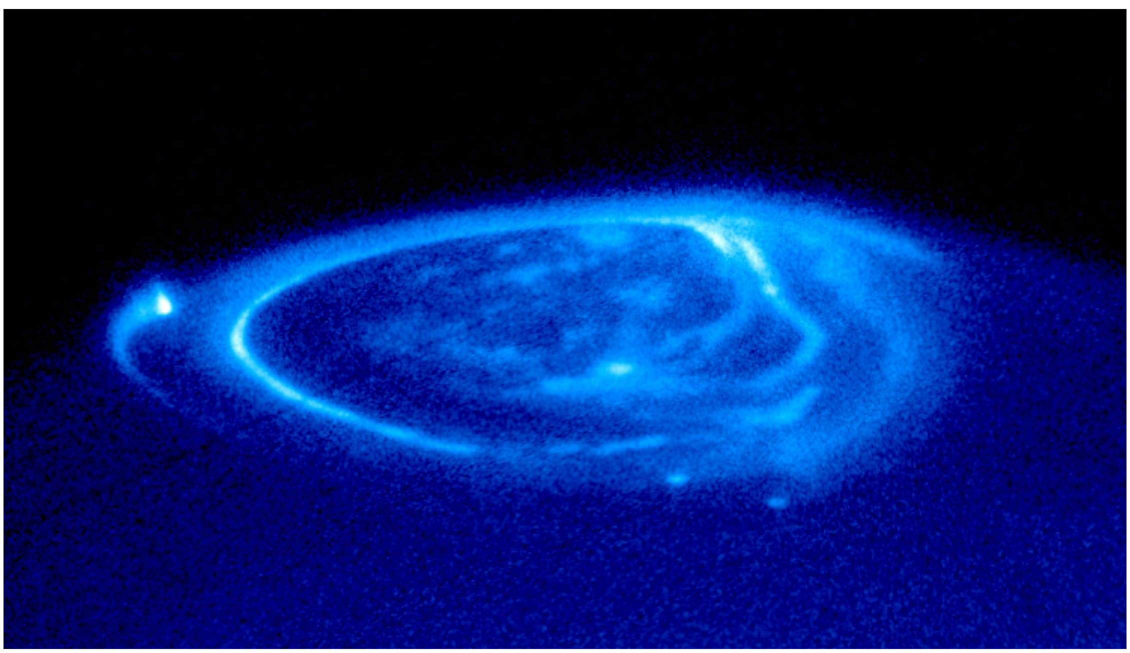

FIGURE 4.3 Jupiter's northern lights as seen in the ultraviolet by the Hubble Space Telescope. In addition to the auroral oval surrounding Jupiter's north magnetic pole, the "footprints" of three of the Galilean satellites are visible. Io's footprint is the prominent spot on the left, while those of Ganymede (near to the center) and Europa (to the lower right of Ganymede's) are less easily seen. (See Figure 4.4 for a schematic view showing the larger context for this image.) Courtesy of NASA/ESA and John Clarke, University of Michigan.

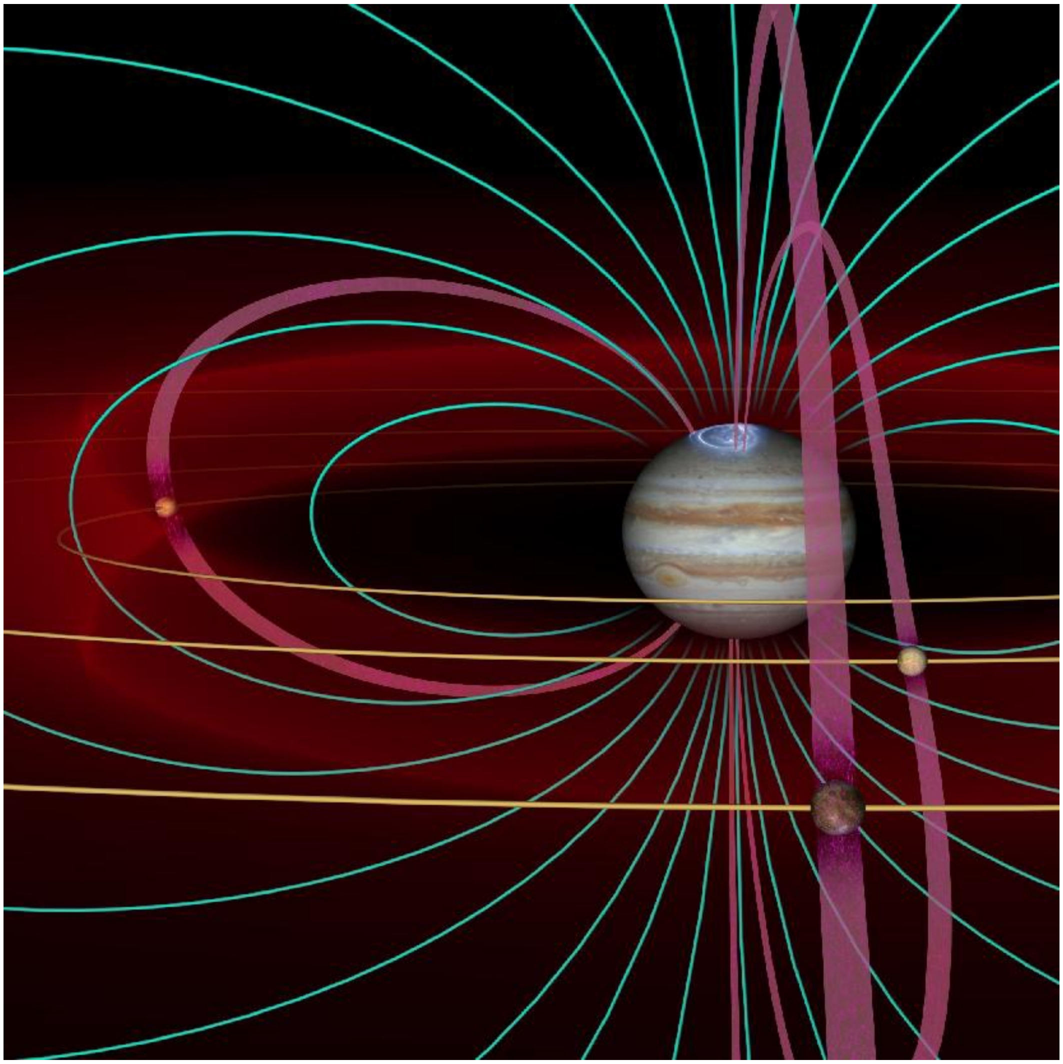

FIGURE 4.4 A schematic illustrating how three of Jupiter's Galilean satellites can leave their footprints on Jupiter's auroral emissions. Strong electric currents, flowing along magnetic flux tubes linking the satelites Io (*left*), Ganymede (*center*), and Europa (*right*) with Jupiter's northern and southern polar regions, stimulate ultraviolet emission in the planet's upper atmosphere. Courtesy of NASA/Boston University.

less dramatic than at Jupiter, is more easily distinguished from competing effects of dipole tilt, which produce a large noise signal at the spin period at Jupiter but are virtually absent at Saturn. Cassini observations at Saturn are thus a critical complement to those of Galileo at Jupiter.

Rotation is also a dominant factor in the magnetospheres of Uranus and Neptune, but with qualitatively new dynamics resulting from the extraordinarily large magnetic dipole tilt angles (59° and 47°, respectively) and offsets (0.3 and 0.55 planetary radii, respectively). The large dipole tilt angles, coupled with the large obliquities of the spin axes (98° and 29°, respectively), produce dramatic variations of the angle of attack between the solar wind and the planetary magnetic dipole.[32] The (acute) angle of attack spans all possible values (0° to 90°) at Uranus and a comparable range (14° to 90°) at Neptune during their orbits around the Sun. At certain favored orbital phases, even the diurnal variation spans a comparable range. For example, during the Voyager 2 encounter in 1989, Neptune's angle of attack varied between 66° (a rather Earth-like value) and 20° (a nearly pole-on geometry) in the course of one-half rotation of the planet. A nearly pole-on geometry (angle of attack <30°) will continue to occur diurnally at Neptune through the late 2020s and will next occur at Uranus during a decade-long window centered around 2014 (and again around 2042). The diurnal flip-flop of these vast magnetospheres between parallel and perpendicular configurations must produce qualitatively new dynamics, because it occurs on a time scale much shorter than the dynamical relaxation time scales of the systems.

The electric current circuit that transmits angular momentum from Jupiter to its distant magnetospheric plasma has many astrophysical analogs. For example, increasing astronomical evidence indicates that the mechanism that powers radio pulsars involves a similar electrodynamic coupling between a central rotating body and a surrounding disk. Solar system formation is a more obvious example. The angular momentum per unit mass of interstellar gas clouds is much greater than that of the solar system, so the system must have lost most of its angular momentum during formation. The outflowing solar wind could account for the loss, provided the gas was forced to corotate with the protosun out to large distances. This fundamental process can be studied in situ today within giant planet magnetospheres and most definitively by a polar-orbiting spacecraft at Jupiter.

Key Questions

Important questions about rings and plasma environments include the following.

Rings

- What are the current physical properties (size distribution, shapes, strength, and nature of aggregations) of particles in the various rings and of distinct regions within the rings?
- What are the most important mechanisms for ring evolution on long and short time scales?
- What are the underlying kinematics and dynamics of the various ring systems? How do self-gravity, viscosity, ballistic transport, and collisions interact?
- What is the chemical composition of the various rings and of distinct regions within the rings?
- What is the current mass flux into the various ring systems? What are the current size, mass, velocity, and composition distributions of the influx population? How did these change with time?
- What are the influences of the magnetospheric and plasma environments of the various rings?
- What do the differences among ring systems tell us about differences in ring progenitors and/or differences in initial and subsequent processes?
- What is the relationship between local ring properties and those properties observable by remote sensing?
- What do planetary rings teach us about nebulas around other stars?

Plasmas

- What is the nature of the electrodynamic coupling between major satellites and the ionospheres of their planets?
- How do the Io plasma torus and analogous structures at other planets convert planetary rotational energy into electromagnetic radiation over a wide range of frequencies?
- How are angular momentum transfer and other global magnetospheric processes revealed through auroral emission features?
- What is the spatial and temporal structure of centrifugally driven plasma transport in a rotation-dominated magnetosphere?
- How and where is the jovian planetary wind generated? Does Saturn have a planetary wind?
- How does the jovian pulsar work? Do other giant planets exhibit pulsar behavior?
- What role does electromagnetic angular momentum transfer, as observed in giant planet magnetospheres, have in solar system formation?

Future Directions

The Cassini mission, given a robust level of science support, is expected to revolutionize our knowledge of both the rings and the magnetosphere of Saturn. Phenomena discovered by Voyagers 1 and 2 in 1980 and 1981 will be explored in depth for the first time, and history tells us to expect the unexpected. For the study of rings and plasmas as for other areas of giant planet studies, our very first priority is to fully exploit the observational capabilities provided by the Cassini orbiter at Saturn.

Jupiter's magnetosphere, because it is the most powerful and the least Earth-like and because of its relative accessibility to both remote and in situ study, is the most promising target for extraterrestrial magnetospheric studies in the next decade. The Galileo mission, despite technical setbacks, filled important gaps in our observational knowledge of Jupiter's magnetospheric structure in the equatorial plane. However, as we have learned from the investigation of Earth's magnetosphere, extrapolations into the third dimension (away from the equatorial plane), in the absence of high-latitude observations, are suspect at best and embarrassingly wrong at worst. The next quantum jump in our understanding of Jupiter's magnetosphere depends on observations in the third (off-equatorial) dimension.

The most important directions for research on the rings and plasma environments of giant planets for the next decade are identified as follows:

- *Measuring the size distribution and composition of ring particles at various locations within the rings.* The Cassini spacecraft will make high-resolution measurements of Saturn's rings. For the ring systems of Jupiter, Uranus, and Neptune, ground-based spectra and stellar occultation data will be required. These measurements will aid in determining the origins and ages of the rings and of the various structures therein. A particle's composition reflects its evolutionary history, and its size determines its lifetime against sputtering and micrometeoroid erosion. Finding the larger bodies that are the likely source for dusty rings is an important objective.
- *Studying the relation among external satellites, embedded moonlets, and structures within the rings.* The observed structures within rings cannot be static, and the relative importance of different evolutionary mechanisms may itself evolve with time. Observations over long time periods are needed to characterize ring kinematics. Observed variations can be coupled with theoretical models to answer outstanding questions such as these: What is perturbing the orbit of Saturn's satellite Prometheus, and what is this satellite's relationship to the F ring? Can the presently observed frequency of meteoroid impacts explain the frequency of the short-lived spokes in Saturn's B ring? Are the Neptune ring arcs indeed confined in corotational resonances, or are they themselves transient?
- *Characterizing the electrodynamic coupling of Jupiter and Saturn with their satellites, rings, and plasma disks.* This is a complicated, three-dimensional puzzle that involves the global configuration of magnetic-field-aligned currents, the identity and velocity distribution of the charged particles that carry these currents, and the magnetospheric structures to which they connect. The solution of this puzzle requires measurements of charged particles, plasma waves, and vector magnetic fields at near-polar latitudes, preferably in conjunction with infrared and ultraviolet imaging of the planet and of its magnetospheric plasma.
- *Determining how internally produced plasma is ejected from a rotation-dominated magnetosphere.* We know that most of Jupiter's magnetospheric plasma comes from Io, deep in the heart of the magnetosphere, and is ultimately lost to interplanetary space in a planetary wind. We know very little of the intervening transport process. The nature of this process is critical to understanding not only the magnetospheres of Jupiter and Saturn but also a much larger class of astrophysical objects. Ordinary plasma particle and field measurements at low altitudes and high magnetic latitudes at Jupiter would revolutionize our understanding of this process.

KEY MEASUREMENT OBJECTIVES FOR GIANT PLANET EXPLORATION

Unanswered questions remain either because they pertain to depths below the reach of remote-sensing instruments or to regions of space close to the planet not penetrated by earlier spacecraft, or because they arose recently as a result of successful missions. New instruments mounted on new platforms and sent to new places will yield the answers. The following measurement objectives, listed in ranked order, have been identified for giant planet research. Jupiter, the prototypical gas giant, is the highest priority for a new mission. Neptune, the prototypical ice giant, is the next-highest priority.

First: Determine the Mass and Size of Jupiter's Core

One theory of giant planet formation says that a rock-ice "seed" of some 10 Earth masses is necessary to attract the lighter gases—hydrogen and helium. Another theory says that Jupiter-sized objects can form as stars do, attracting gas, ice, and dust directly from the nebula. The latter process produces an object without a core. The two scenarios have vastly different consequences for giant planet and solar system formation. The core manifests itself both in the rotational bulge, which is the response of the planet to its own rotation, and in the tidal bulge, which is the response of the planet to the gravitational pull of the satellites. Both bulges have signatures in the planet's gravity field, which can be measured from an inclined orbit with periapse close to the planet. An independent technique uses distortions of the magnetic field near the pole to infer the core's radius, in analogy with Earth's magnetic field, which reveals the inner core's radius.[33] A low-periapse polar-orbiting spacecraft equipped with a radio transponder and vector magnetometer is required.

Second: Measure Elemental Abundances (H, He, O, C, N, S)

The water abundance (hence, the O/H ratio) in Jupiter's atmosphere is uncertain by an order of magnitude, even though oxygen is expected to be the third-most-abundant element after hydrogen and helium. Water plays an important role in giant planet formation. The O/H ratio tells us how giant planets got their volatiles (H_2O, CH_4, NH_3, and H_2S) and, in particular, the extent to which the volatiles were carried in from beyond Neptune's orbit to the inner solar system on icy planetesimals. Water is also important to the meteorology of giant planets, as it is on Earth. The Galileo probe penetrated below the jovian clouds, but the composition was still varying when the probe reached its maximum depth at 24 bars. The fact that the probe entered an unusually hot, dry region hindered the interpretation. Better coverage in latitude and penetration to greater depth are needed. This need can be met with the following two complementary approaches.

- *Multiple entry probes carrying mass spectrometers.* A dedicated spacecraft should be able to carry three probes that enter within 30 degrees of the equator and reach depths of 100 bars. The carrier makes a polar pass where it collects the data from each probe, and then transmits to Earth. Having only three probes is a limitation, but it is sufficient to resolve the ambiguity left by the single Galileo probe. Ammonia is measured separately by monitoring the attenuation of the probe's radio signal (measuring ammonia by mass spectrometry is not accurate because it coats the walls of the chamber).
- *Microwave radiometry.* This technique uses thermal emission from the planet at wavelengths between 10 and 100 cm to measure the water and ammonia abundance from 10 to hundreds of bars. To avoid interference from Jupiter's radiation belts, the measurement must be made when the spacecraft is less than several thousand kilometers above the tops of the clouds. A polar-orbiting spacecraft is best because it gives latitude and longitude coverage while avoiding radiation-belt and ring-particle hazards. Interpretation of the radiometry results is facilitated by knowledge of the temperature profile, which can be measured by an entry probe. Multiprobes provide ground-truth for interpreting the radiometer observations, which in turn provide global coverage that is not obtainable from a limited number of probes.

Third: Investigate Deep Winds and Internal Convection

Jupiter's jet streams and oval storms may get their 100-year longevity from massive jet streams and convection cells in Jupiter's interior. The degree of coupling between motions in the visible atmosphere and the interior depends on the thermal structure, which itself is unknown. A probe can measure both thermal structure and winds, the latter using the Doppler shift in the probe's radio signal. A probe can also measure clouds, sunlight, and gaseous composition, but only to depths of 100 bars, at least for Jupiter. Motions at deeper levels may be inferred from the planet's gravity field. For instance, if the observed jet streams extend down to kilobar pressures, the gravity field will look noticeably "rougher" than if the interior is in solid body rotation.[34]

An orbiting spacecraft that skims close to the top of the atmosphere can measure this fine structure of the gravity field. It could also measure the fine structure of the magnetic field, which might tell us if the winds extend to the depth where the fluid becomes an electrical conductor: The tilted dipole field appears to be time-dependent in the reference frame of the moving fluid, and the time-dependence produces electrical currents that cause observable changes in the field.[35]

Fourth: Map the Structure of Magnetic Field

The goal is to understand how planetary dynamos operate. Previous spacecraft did not spend enough time close to Jupiter or any of the other giant planets to measure the fine structure and temporal variations of the magnetic field. The external field can be extrapolated down to the level where the fluid becomes an electrical conductor. At Earth this level is the liquid iron core, and there the spectrum of the magnetic field is flat—the different harmonic components of the field all have comparable amplitudes. This may be a fundamental property of planetary dynamos. The fields of the giant planets provide an opportunity to find out.

Fifth: Explore Polar Magnetospheres

The solar wind, the satellites, the rings, and the planet can all act both as sources and as sinks of charged particles that populate the magnetosphere. The polar regions, where magnetospheric particles interact with the planetary atmosphere to produce the aurora and related radio emissions, are particularly important. There, magnetic field lines from the distant magnetosphere and from interplanetary space reach the planet's atmosphere. Previous spacecraft missions to the giant planets have not explored the auroral zone because they were designed to visit satellites in the equatorial plane and to avoid radiation and ring particle hazards close to the planet. However, a polar orbiter with a near-equatorial periapse just above the cloud tops will traverse the polar region at a distance of 2 to 3 planetary radii from the planet's center, while avoiding the rings and most of the radiation belts (Figure 4.5). Existing instruments can sample the composition, density, and velocity distribution of the charged particles and learn where they come from. Jupiter is interesting because it has the largest and most powerful magnetosphere and because our knowledge of it is largely restricted to the equatorial plane. Neptune is interesting because the tilt of the field exposes the polar cusp to the solar wind on every rotation. This 16-hour periodicity allows one to see the sources and sinks in operation on very short time scales. A Neptune orbiter that reaches high latitudes could take advantage of this opportunity.

Sixth: Determine the Properties of Planetary Rings

Composition, particle size, number density, collisional efficiency, and collective behavior are some of the most important properties of planetary rings. The Cassini orbiter has the potential to do an exquisite job with the most massive rings in the solar system. A Cassini extended mission would provide data on decadal changes, including thermal effects when the rings are edge-on to the Sun, dynamical effects when nearby satellites pass in their orbits, and secular changes brought about by collisions with interplanetary bodies. However, celestial mechanics prevents Cassini from hovering over the rings. Such hovering would allow one to follow individual ring particles as they collide with each other, but technological developments are needed to accomplish this.

Seventh: Map Atmospheric Properties as Functions of Depth, Latitude, and Longitude

The Cassini mission will provide a wealth of new information about the three-dimensional structure of Saturn's atmosphere. However, Earth-based telescopic observations are an essential complement to in situ studies at Jupiter and Saturn and are the only source of such information for Uranus and Neptune in the next decade. Three-dimensional distributions of atmospheric composition, temperature, aerosols, winds, and auroral emissions

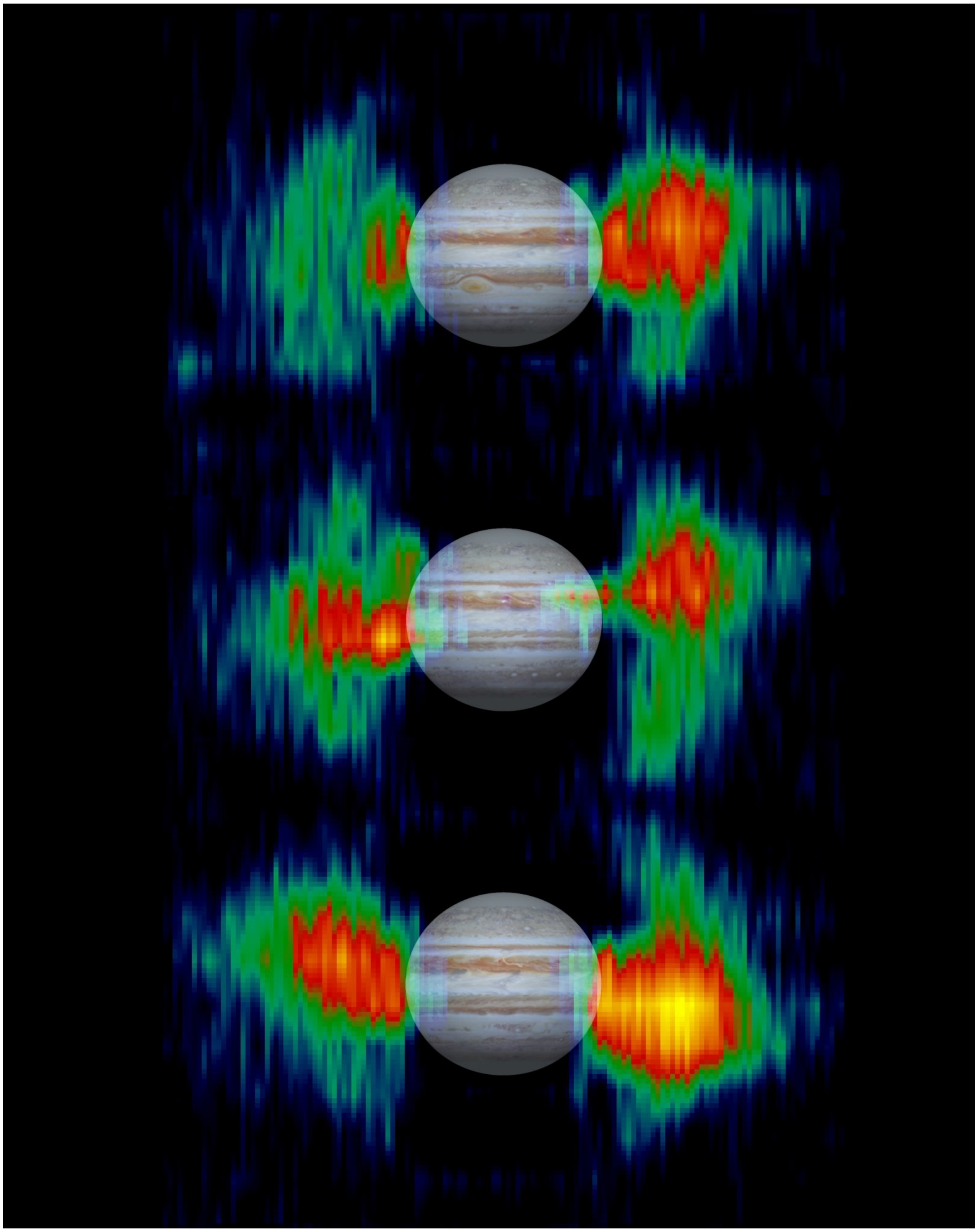

FIGURE 4.5 Cassini's radar system doubled as a radio telescope to collect these images showing the variations in Jupiter's trapped radiation belts over a 10-hour period. The radio emission has a wavelength of 2.2 cm and originates from electrons trapped in Jupiter's intense magnetic field. The belts wobble with respect to the superposed optical images because Jupiter's magnetic axis is inclined with respect to its rotation axis. Courtesy of NASA/JPL.

are poorly known for the outer planets. This situation can be improved dramatically in the next decade by utilizing large ground-based telescopes with adaptive optics, advanced detectors, and the expanded wavelength coverage available from space-based telescopes.

SPACE MISSIONS FOR GIANT PLANET EXPLORATION

Space Missions

The Cassini orbiter is scheduled to begin its exploration of the Saturn system in late 2004. The success of this historic effort is a matter of the highest scientific priority, and it should also be a matter of the highest programmatic importance.

The Giant Planets Panel has identified a single medium-class new mission that addresses most of the key questions described above for a gas giant—a Jupiter polar orbiter with three atmospheric entry probes. This mission requires only incremental technological development. It can and should be launched in this decade. For the longer term, the panel has identified a single large-class mission that addresses most of the key questions for an ice giant—a Neptune orbiter with multiple entry probes. The Neptune mission, among others, requires new technology development that should be initiated in this decade to enable consideration in the following decade. Table 4.1 summarizes how these missions and other activities address the key science questions discussed above.

Jupiter Polar Orbiter with Probes

The Jupiter Polar Orbiter with Probes (JPOP) mission combines several smaller missions that have recently been proposed or studied by NASA teams. Combining them as one mission reduces transportation costs and enhances the science return, because the measurements complement each other in important ways. The elements of the mission are as follows:

- A polar orbiter (periapse $<1.1\ R_J$) spacecraft for atmospheric remote sensing, gravity analysis, particles and fields measurements, and probe data relay; and
- Three atmospheric probes that can penetrate to the 100-bar pressure level and that can sample a range of latitudes within 30 degrees of the equator for atmospheric sounding.

JPOP carries a microwave radiometer that is used for remote sensing of atmospheric composition when it is inside the radiation belts; thus, the periapse of the orbiter must be close to the planet. The polar inclination and low periapse are also essential to avoid radiation and ring hazards. The radiometer obtains estimates of the water and ammonia abundances to depths of hundreds of bars. The pole-to-pole coverage complements the mass spectrometers on the probes, which sample a range of latitudes within ±30 degrees. The mass spectrometers on the probes provide ground-truth for the microwave radiometer. The probes measure composition, winds, temperatures, clouds, and sunlight as functions of pressure to 100 bars.

After dropping off the probes and relaying their signals to Earth, JPOP spends a year or more in a highly inclined orbit with periapse near the equatorial plane $<1.1\ R_J$ from the planet center. It measures the magnetic field, charged particles, and plasma waves close to the planet. Radio occultations probe the atmospheric dynamical structure. The orbit itself is sensitive to the fine structure of the gravity field. Both the axisymmetric part due to Jupiter's internal mass distribution and the nonaxisymmetric part due to satellite-induced tides are measured. The microwave radiometer, away from periapse, provides the first three-dimensional map of Jupiter's radiation belts. Additional remote sensing (ultraviolet, visible, infrared) would be desirable but is not critical to the success of the mission.

Cassini—Nominal Mission

The performance of the Cassini spacecraft and instruments during the December 2000 Jupiter flyby bodes well for the potential success of the Cassini orbiter mission at Saturn. To realize this potential, hard decisions have to be made concerning science priorities. Past economies and added taxes have affected the run-out costs of this program, threatening the community's ability to ingest and interpret the data. As the mission progresses and the capabilities of the instrument complement are known, the run-out budget should be enhanced to allow optimal analysis by team members and the larger science community.

Cassini—Extended Mission

After the nominal Cassini mission ends, coverage of many parts of the Saturn system, including Titan's surface and the polar regions of the planet and its magnetosphere, will be incomplete. A Cassini extended mission should be formulated and priced in order to obtain optimal science-to-cost ratio. The Cassini Saturn science complements that from the proposed Jupiter Polar Orbiter with Probes mission. Critical choices should be made to optimize the total yield from these missions.

Neptune Orbiter with Probes

The objectives of this longer-term mission span the planet, rings, magnetosphere, and satellites, particularly Triton. The spacecraft would carry remote-sensing instruments as well as instruments to sample particles and fields. Compared with the Jupiter Polar Orbiter with Probes, the Neptune mission would be more comprehensive, as befits a planet about which less is known. Trade-offs would have to be made among the orbit, payload, power, telemetry, and other resources. Satellite objectives are described in other chapters. Here the panel describes objectives arising from the planet, the rings, and the magnetosphere.

As with Jupiter, knowing the volatile abundances has high priority. The cloud base for water may be deep within the planet, so the atmospheric abundance might reflect the saturation vapor pressure rather that the bulk water abundance of the interior. Other volatiles such as CH_4, NH_3, and H_2S may have cloud bases within the range of probes and microwave remote-sensing observations, so it would be possible to sample the well-mixed planetary interior for these compounds. Both the gravity field and magnetic field are of great interest. Voyager showed that the magnetic field is "rougher" than that of Jupiter or Saturn, suggesting that the dynamo region is closer to the surface. Low periapse altitude, at least on some of the orbits, is highly desirable. Comprehensive sampling of the magnetosphere in latitude, longitude, altitude, and local time has high priority. Neptune offers a unique opportunity to study the interaction of the magnetosphere with the solar wind on diurnal time scales.

Within the neptunian rings, the vertical and radial structure is poorly defined and the composition is undetermined. More than any other ring system, Neptune's rings illustrate close dynamical associations between dusty rings and a set of small, embedded satellites. The surfaces of the inner ring-region satellites, orbiting within the Roche zone, should record the stresses they have undergone. This is especially true for Galatea, the satellite responsible for confinement of the ring arcs. Bringing the understanding of the neptunian ring system up to a level similar to that of the Saturn and jovian rings will allow comparative ring studies to better understand why the ring systems differ.

Enabling technologies for a Neptune Orbiter with Probes mission (see below) include nuclear electric propulsion and power sources, enhanced telemetry, improved heat shields, lightweight instruments for entry probes, and possibly aerocapture.

TABLE 4.1 Relationships of Recommended Initiatives to Key Science Questions for Giant Planet Exploration

		Mission								
Class of Question	Scientific Themes	Jupiter Polar Orbiter with Probes	Cassini Nominal Mission	Cassini Extended Mission	Earth-Based Orbiting Facilities	Neptune Polar Orbiter with Probes	Saturn Ring Observer	Uranus Orbiter with Probes	Analysis and Modeling	Laboratory
Theme 1. ORIGIN AND EVOLUTION										
Solar-System Giant Planets										
Paradigm altering	How did the giant planets form?	xxx	xx	xxx	x	xxx	x	xxx	xx	xx
Paradigm altering	What are the orbital evolutionary paths of giant planets?	xxx	xx	xxx	o	xxx	xx	xxx	xxx	o
Pivotal	Does Jupiter have a rock-ice core?	xxx	o	o	o	o	o	o	xx	x
Pivotal	What are the elemental compositions of the giant planets?	xxx	xx	xx	x	xxx	o	xxx	xx	x
Pivotal	What are the internal structures and dynamics of giant planets?	xxx	xx	xxx	xx(1)	xxx	o	xxx	xx	xx
Extrasolar Giant Planets and Brown Dwarfs										
Pivotal	How can we use the giant planets in our solar system to calibrate spectroscopic observations (optical, infrared, radio) of extrasolar giant planets?	xxx	xx	xx	xx	xxx	o	xxx	xxx	x
Foundation building	Around what types of stars do we find giant planets?	AP	AP	AP	AP	AP	AP	AP	AP	o
Foundation building	Are multiple giant planets common in stellar systems?	AP	AP	AP	AP	AP	AP	AP	AP	o
Foundation building	In what ways do giant planets differ from brown dwarfs?	AP	AP	AP	AP	AP	AP	AP	AP	o
Foundation building	What are the properties of extrasolar giant planets (radii, effective temperatures, compositions, clouds, moons, winds, magnetic fields, heat flows)?	AP	AP	AP	AP	AP	AP	AP	AP	o
Theme 2. INTERIORS AND ATMOSPHERES										
Interiors										
Pivotal	What is the nature of phase transitions within the giant planets?	xxx	xx	xxx	xx(1)	xxx	o	xxx	xx	x
Pivotal	How is energy transported through the deep atmosphere? Do radiative layers exist?	xxx	xx	xx	xx(1)	xxx	o	xxx	xx	x
Pivotal	How and where are planetary magnetic fields generated?	xxx	xx	xx(2)	x(1)	xxx	o	xxx	xxx	o
Foundation building	What is the nature of convection in giant planet interiors?	xxx	xx	xx(2)	xx(1)	xxx	o	xxx	xxx	o
Foundation building	How does the composition vary with depth?	xxx	xx	xx(2)	x(1)	xxx	o	xxx	xx	o

Atmospheres										
Pivotal	What energy source maintains the zonal winds, and how do they vary with depth? What role does water and moist convection play?	xxx	xx	xx	x	xxx	o	xxx	xx	x
Pivotal	What physical and chemical processes control the atmospheric composition and the formation of clouds and haze layers?	xxx	x	x	x	xxx	o	xxx	xx	x
Foundation building	How and why does atmospheric temperature vary with depth, latitude, and longitude?	xxx	xx	xx	x	xxx	o	xxx	xx	x
Foundation building	How does the aurora affect the global composition, temperature, and haze formation?	x	xx	xx	x	x	o	x	xx	x
Foundation building	What produces the intricate vertical structure of giant planet ionospheres?	xx	xx	xx	x	xx	o	xx	xx	x
Foundation building	At what rate does external material enter giant planet atmospheres, and where does this material come from?	o	x	x	x	o	o	o	xx	x
Foundation building	What can organic chemistry in giant planet atmospheres tell us about the atmosphere of early Earth and the origin of life?	x	x	x	x	x	o	x	xx	x
Theme 3. RINGS AND PLASMAS										
Rings										
Paradigm altering	What are the most important mechanisms for ring evolution on long and short time scales? How do self-gravity, viscosity, ballistic transport, and collisions interact?	o	xx	xxx	x	xxx	xxx	xxx	xxx	x
Pivotal	What do planetary rings teach us about nebulas around other stars?	AP	AP	AP	AP	AP	AP	AP	AP	AP
Foundation building	What are the present physical properties (composition, size distribution, shapes) of particles in the various distinct regions within the various rings?	o	xxx	xxx	x	xxx	xxx	xxx	xx	xx
Foundation building	What is the present mass flux into the various ring systems? What are the present size, mass, velocity, and composition distributions of the influx population?	o	xx	xx	o	xx	xx	xx	x	o
Foundation building	What is the relationship between local ring properties and those properties observable by remote sensing?	o	xxx	xx	xx	xx	xxx	xx	xx	x
Foundation building	How fast are angular momentum and energy being transferred among rings and moons?	o	xx	xx	x	xx	xxx	xx	xx	o
Foundation building	What is the influence of magnetospheric plasma on the rings?	o	xx	xx	o	xx	xxx	xx	x	o
Plasmas										
Paradigm altering	What is the nature of the electrodynamic coupling between major satellites and the ionospheres of their planets?	xxx	xxx	xx	x	xx	o	xx	xx	o
Pivotal	What is the spatial and temporal structure of centrifugally driven plasma transport in a rotation-dominated magnetosphere?	xxx	xx	xx	o	x	o	x	xx	o
Pivotal	What role does electromagnetic angular momentum transfer, as observed in giant planet magnetospheres, have in solar system formation?	AP	AP	AP	o	AP	o	AP	AP	o
Foundation building	How do the Io plasma torus and analogous structures at other planets convert planetary rotational energy into electromagnetic radiation over a wide range of frequencies?	xx	xx	x	x	x	o	x	xx	o
Foundation building	How are angular-momentum transfer and other global magnetospheric processes revealed through auroral emission features?	xxx	xx	xx	o	x	o	x	xx	o
Foundation building	How and where is the jovian planetary wind generated? Does Saturn have a planetary wind?	x	xxx	xx	o	o	o	o	xx	o
Foundation building	How does the jovian pulsar work? Do other giant planets exhibit pulsar behavior?	xxx	xxx	xx	x	x	o	x	xx	o

NOTE: o, not applicable; x, significant advance in understanding; xx, major advance; xxx, breakthrough; AP, results relevant to NASA's Astronomical Search for Origins program; (1), assumes P-modes will be detected; and (2), assumes high-inclination orbits.

Other Mission Concepts

Two other promising concepts for longer-term missions are listed here, without any ranking. As is the Neptune Orbiter with Probes, they are dependent on the development of enabling technologies.

Saturn Ring Observer

On a Saturn Ring Observer mission, advanced propulsion would be used to hover close above the ring plane for long-term study of collisions and other microphysical processes.

Uranus Orbiter with Probes

The science objectives and payload of a Uranus Orbiter with Probes mission would be similar to those of the Neptune Orbiter with Probes mission.

Key Enabling Technologies and Earth-Based Facilities for Giant Planet Exploration

Technology Development

Two incremental technological developments are needed for atmospheric probes to the 100-bar pressure level at Jupiter during the present decade:

- Lightweight heat shields, and
- Lightweight (a few kilograms) mass spectrometers.

To enable high-priority missions in later decades, the following technological goals need to be pursued vigorously in the present decade:

- Implement nuclear-electric propulsion;
- Obtain enhanced telecommunications, including large microwave arrays and/or optimization of the NASA's Deep Space Network (DSN); and
- Determine the feasibility of implementing aerocapture in giant planet atmospheres.

In addition, outer-planet missions require nuclear-electric power sources such as radioisotope power systems (RPSs). Although the technology is well in hand, procurement steps must be taken to ensure availability.

Earth-Based Facilities

Important Earth-based facilities include large ground-based telescopes, survey telescopes, space telescopes, and large radio arrays. All of these have general astronomical applications. The study of giant planets around other stars is a booming and important field, which will rely increasingly on solar system giant planets for calibration. Here the panel emphasizes what can be learned about our own giant planets from these Earth-based facilities.

Giant (20- to 30-m) Segmented Mirror Telescope

The adaptive optics (AO) capability will provide diffraction-limited imaging of solar system objects. The large light-gathering power of the telescope allows high-resolution spectroscopy of the outer planets, which is critical for determining altitude variations of their atmospheric properties. The planetary community needs to help define the capabilities of the AO system and the specific instruments that will be developed for this telescope. The ability to track moving targets is important for solar system studies in general.

Dedicated Planetary Telescope and/or Refurbished IRTF

Some areas of planetary science are best served by long-term monitoring. Examples include dynamic features in giant planet atmospheres, the jovian magnetosphere and its response to volcanic outbursts from Io, and spacecraft missions that need Earth-based support. These activities need large blocks of observing time. The solution is to have a dedicated planetary telescope such as NASA's Infrared Telescope Facility (IRTF), although that telescope needs refurbishment to keep up with modern demands and to utilize modern technology.

Space Telescopes

Although ground-based telescopes with AO systems can surpass the diffraction-limited imaging capabilities of space-based telescopes, the latter allow one to observe in the ultraviolet and far infrared where ground-based telescopes cannot. Space-based telescopes also have a more nearly continuous duty cycle. Planetary scientists must be included in early planning and development to ensure that space telescopes have instruments and tracking capabilities that serve solar system research objectives.

Square-Kilometer Array

The Square-Kilometer Array (SKA) is a proposed international radio astronomy venture that parallels enhancements that are being discussed for the Deep Space Network. The DSN is primarily for telemetry and the SKA is primarily for listening, but it would be desirable if the two arrays were compatible and could be arrayed together for special events and unusual scientific opportunities.

RECOMMENDATIONS OF THE GIANT PLANETS PANEL TO THE STEERING GROUP

The study of giant planets stands at the threshold of a new era. Even as we complete the first systematic explorations of Jupiter and Saturn with orbiting spacecraft, we are witnessing an explosion in the number of known giant planets around other stars. As we struggle to comprehend the diversity of planetary systems discovered elsewhere in our galaxy, we are reminded of certain fundamental things that we do not yet know about our own impressive system of four giant planets. For example, we do not know if Jupiter has a solid core, or if it contains enough water to support standard theories of solar system formation and evolution. We do not fully understand the mechanism that produces and sustains the banded atmospheric structure or how deep that structure goes, or how it might affect the distant spectral signature of a giant planet under the most general range of possible conditions. We are just beginning to probe the complexities of the many-body gravitational interactions that shape the rings, and the magnetohydrodynamic interactions that shape the magnetospheres, although both are likely to be important during the course of stellar and planetary evolution. On the other hand, we know far more than we did two decades ago. The legacy of the Voyager, Galileo, and (soon) Cassini missions and concurrent ground-based work is that we now know how to formulate the questions presented above in a precise manner, and indeed, we know how to find the answers.

As far as we know, there are two generic types of giant planet—the gas giants like Jupiter and Saturn and the ice giants like Uranus and Neptune. A better understanding of the nature of both types is needed, both to answer fundamental questions concerning the formation of the solar system and to guide the interpretation of observations of other planetary systems.

In assigning priorities for future missions to the giant planets, a variety of factors must be and have been considered. Long travel times and tight mass and communication constraints are a given with missions to the outer planets. The need for near-term development of enabling technologies for longer-term missions must be considered. Above all, it must be recognized that extrasolar planets will increasingly become a focus of both scientific and popular attention, as evidenced by the selection of Kepler—a Discovery mission designed to search for extrasolar planets by looking for the luminosity variations they may cause as they transit the disks of their parent stars. Many more extrasolar planets will be detected in the next decade. Some will be imaged, and their spectra will be partially resolved. To provide critical ground-truth for these exciting discoveries, NASA should pursue a parallel program of close-up exploration and analysis of our own giant planets. These two lines of investigation can be, and should be, synergistic.

For the next decade, the Giant Planets Panel recommends the following initiatives, in ranked order:

1. *Characterize the gas giant Jupiter.* The centerpiece of this effort should be a dedicated mission such as the polar orbiter with three entry probes described above. Earth-based observational and theoretical efforts would, as always, be essential complements to this spacecraft mission. The mission is scientifically focused and technologically feasible with only modest improvements to available technology. It addresses several outstanding questions that are fundamental both for understanding the solar system and for calibrating observations of other planetary systems.

2. *Exploit the capabilities of the Cassini orbiter at Saturn.* Every effort should be made to maximize the scientific yield from the Cassini orbiter mission. As the mission progresses, the quality of the data should be assessed and the level of science support within the instrument teams should be enhanced accordingly. Funding should be provided to the research community for data analysis, and a plan for extending the primary mission should be developed on the basis of new science that can be achieved.

3. *Enhance the productivity of Earth-based studies.* Many of our key questions can be addressed effectively with Earth-orbiting telescopes and ground-based telescopes utilizing adaptive optics. Planetary scientists should be actively engaged in defining the capabilities and scheduling of these advanced observing platforms. Some questions require a dedicated telescope for systematic long-term monitoring. The maintenance and refurbishing of the IRTF for this purpose is a continuing priority. Maximizing the science return from both in situ and Earth-based observations requires a robust concurrent program of data analysis and modeling efforts.

4. *Prepare for future exploration of the ice giant Neptune.* Preparations must begin in this decade to enable a future mission to Neptune, as described above. Technology needs for such a mission include nuclear-electric propulsion and advanced power sources, enhanced telecommunications, and lightweight (a few kilograms) mass spectrometers and heat shields for entry probes.

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